Proton-driven plasma wakefield acceleration

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- Motivation : particle physics; large accelerators
- General concept : proton-driven plasma wakefield acceleration
- Towards a first test experiment at CERN
- Future plans and challenges

HPL User Meeting, 15–17 December 2010

Motivation

Motivation

• The use of (large) accelerators has been central to advances in particle physics.

• Culmination in 27-km long LHC (pp); a future e^+e^- collider is planned to be 30–50-km long. A new pp machine ?

• Such projects are (very) expensive; can we reduce costs ? are there new technologies which can be used or developed ?

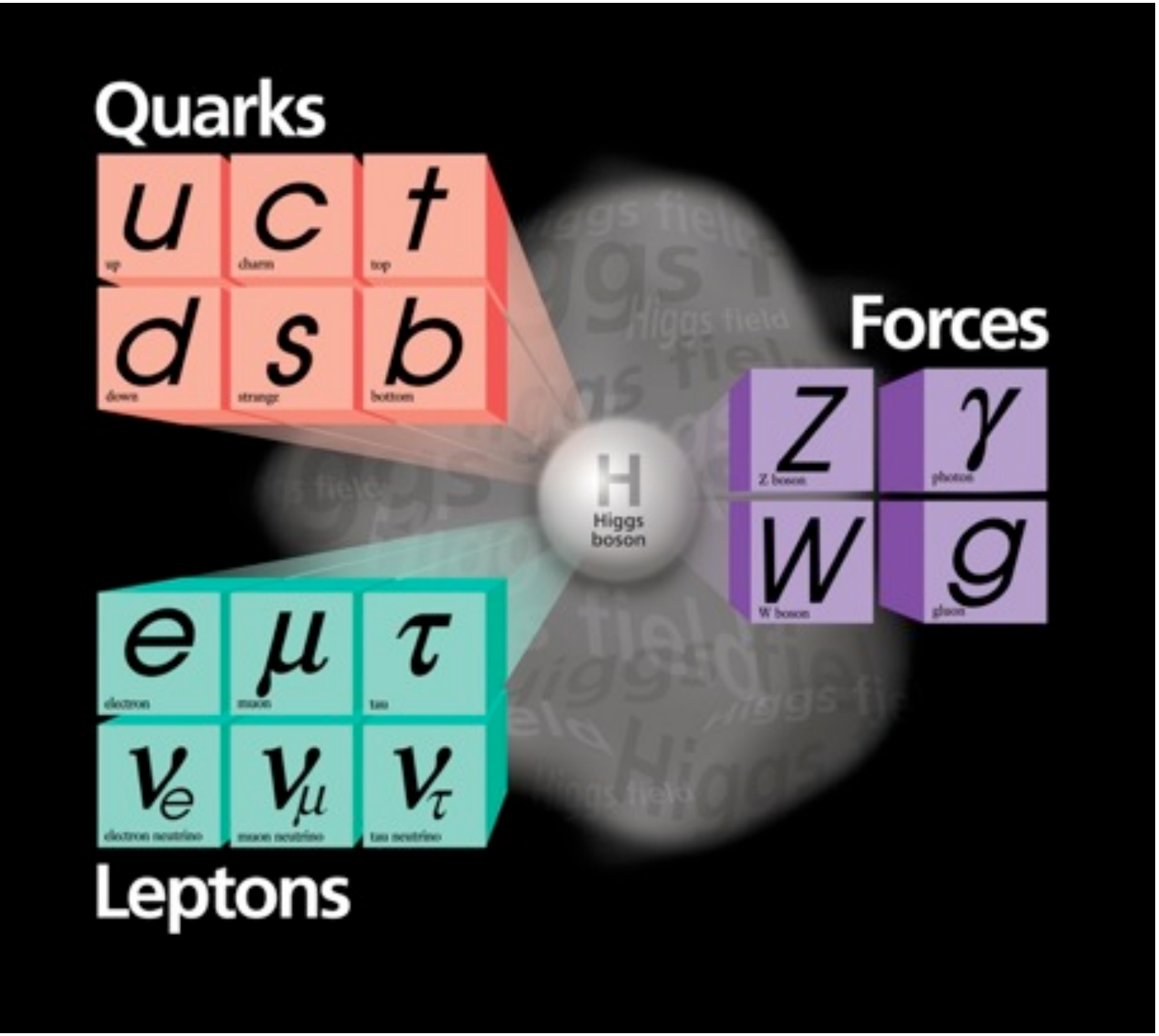
• Accelerating gradients achieved in the wakefield of a plasma look promising, but :

- we need high-energy beams (~ TeV);
- high repetition rate and high number of particles per bunch;
- large-scale accelerator complex.

• Ultimate goal : can we have a multi-TeV lepton collider of a few km in length ?

• A challenge for accelerator, plasma and particle physics.

Particle physics 101—The Standard Model



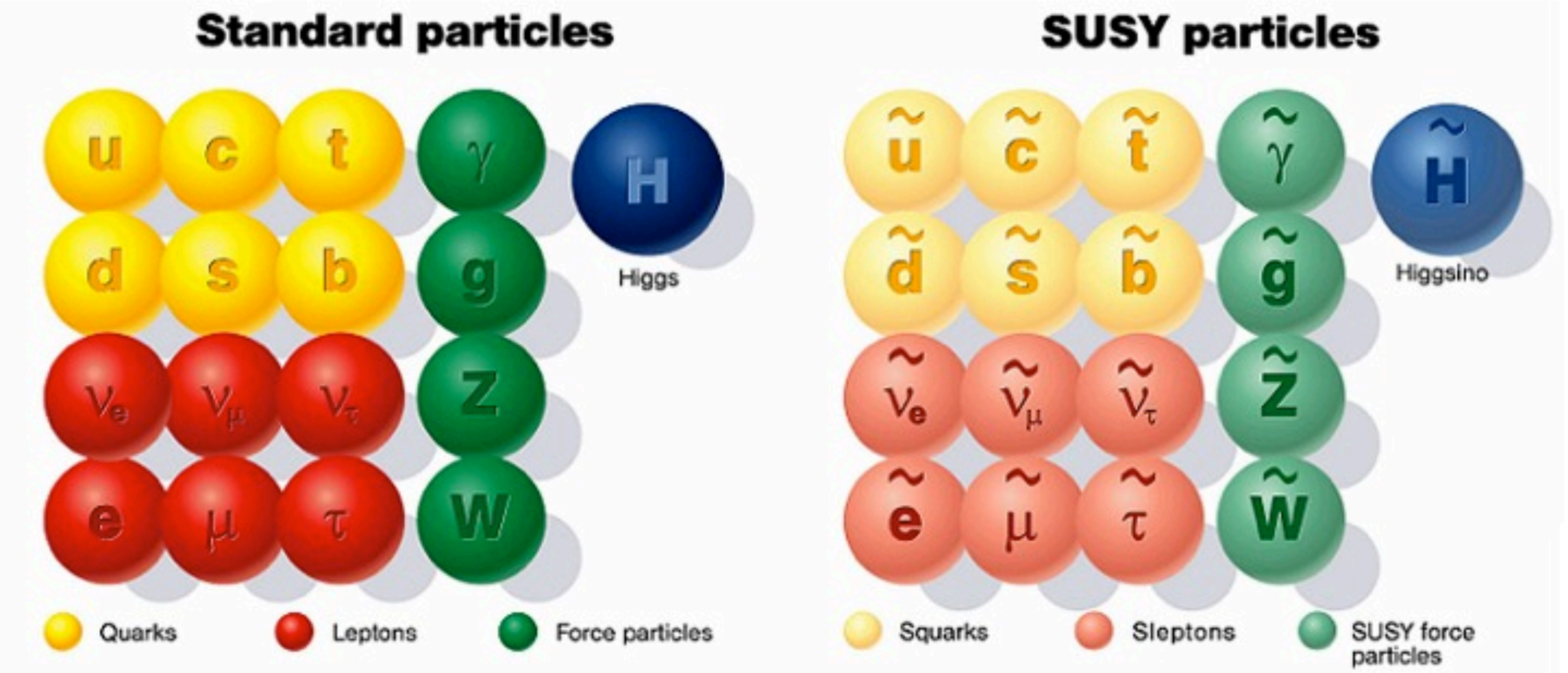
We have :

- fundamental point-like particles.
- force carriers.
- field theories which describe measurements.
- data and theory with a precision up to 1 in 10^{10}.

Still unexplained :

- where is the Higgs particle ?
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (5% of Universe) ?
- can we unify the forces ?

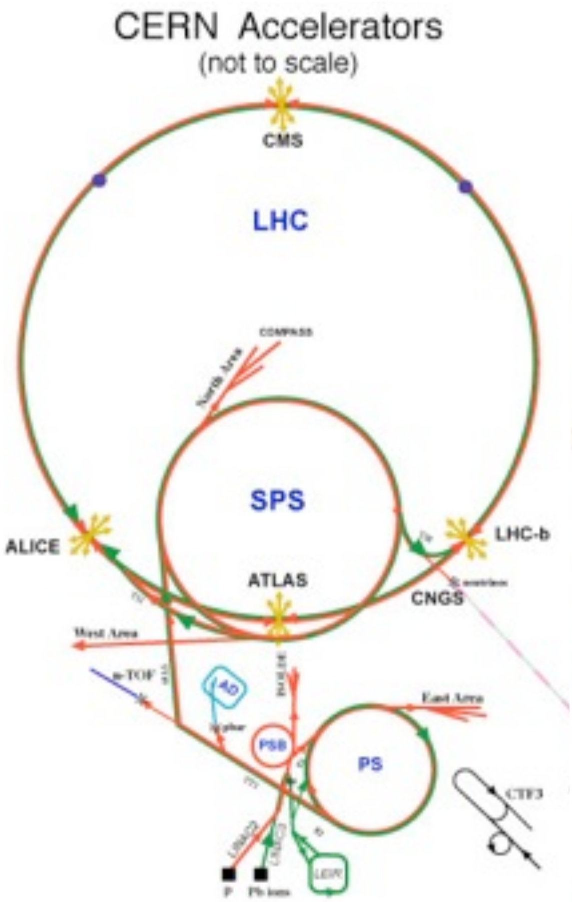
Particle physics 101—Supersymmetry (e.g.)

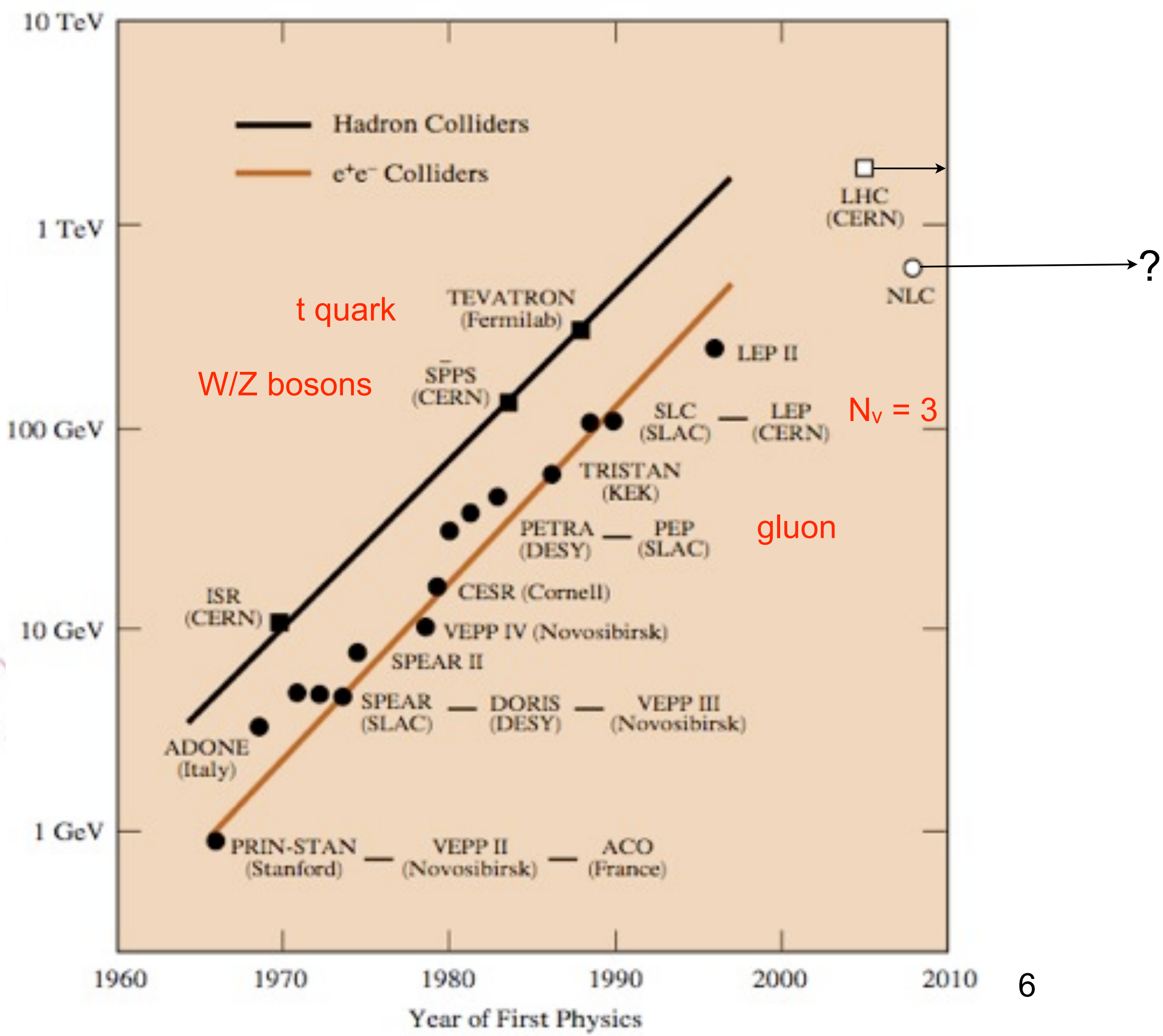


Hope to discover Higgs particle and e.g. Supersymmetry at the LHC and future colliders.

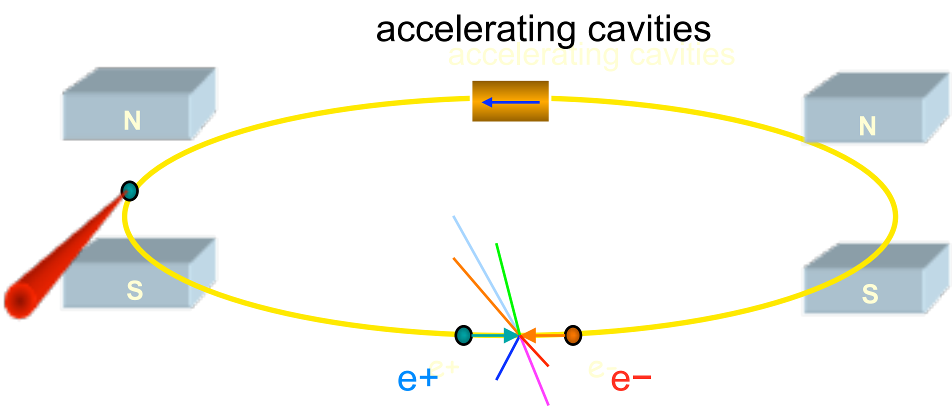
Precision environment of a lepton collider essential for measuring properties of newly-discovered particles or phenomena.

Collider history



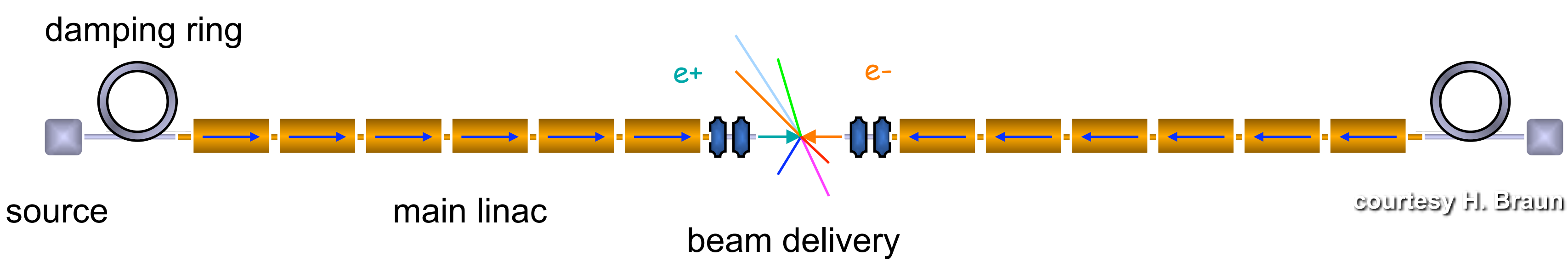


Conventional accelerators



Circular colliders :

- Many magnets, few cavities so strong field needed;
- High synchroton radiation;
- High repetition rate leads to high luminosity.



Linear colliders :

- Few magnets, many cavities so efficient RF power production needed;
- Single pass so need small cross section for high luminosity and very high beam quality;
- The higher the gradient, the shorter the linac.

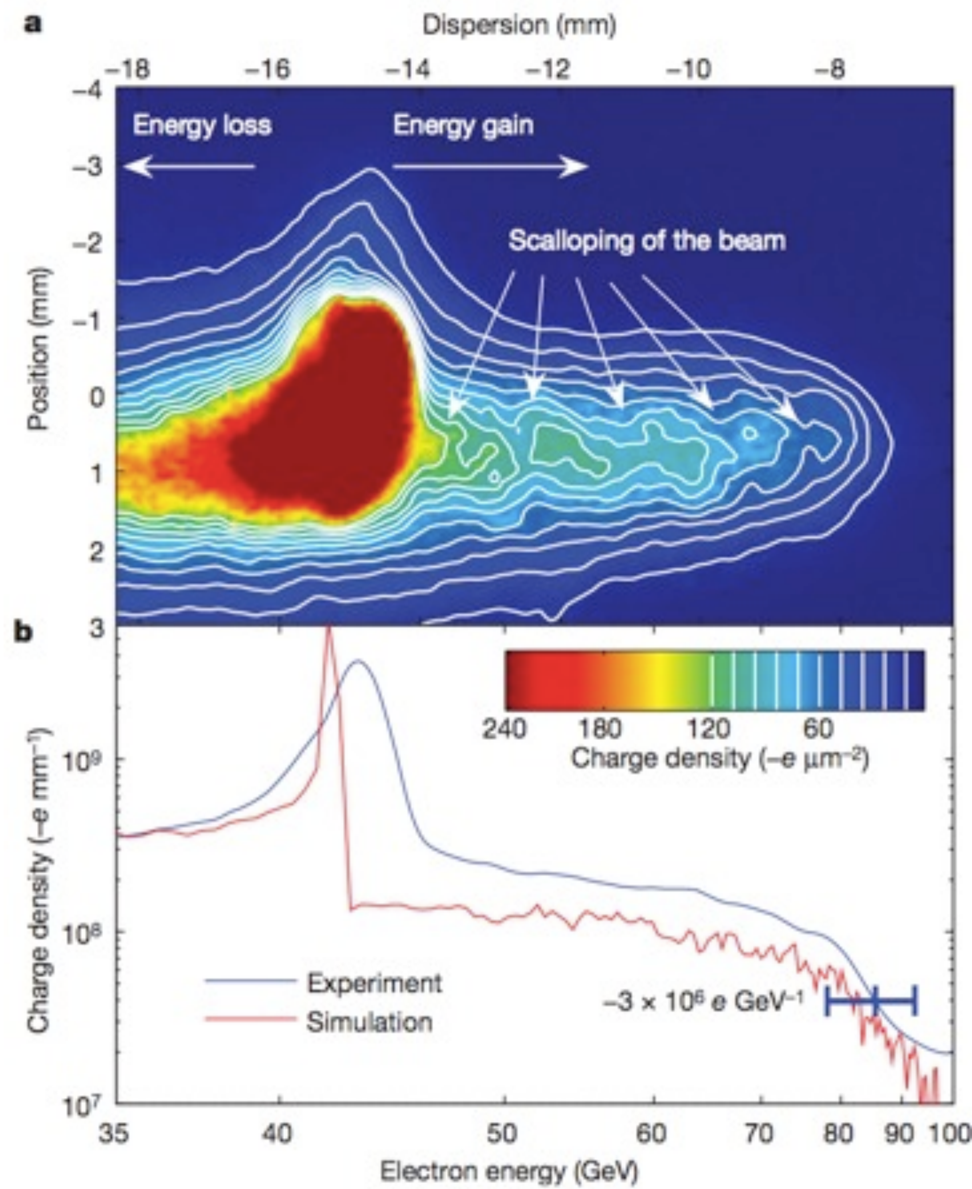
Current / proposed accelerators

Parameter	ILC	CLIC	LHC
E_{CM} (TeV)	0.5–1	3	14
Bunch separation (ns)	369	0.5	25
No. particles/bunch	2×10^{10}	4×10^{9}	1×10^{11}
No. bunches/train	2625	312	2808
Repetition rate (Hz)	5	50	–
Accelerating gradient (MV/m)	35	100	5
Beam size (nm)	640 × 5.7	45 × 0.9	16000 × 16000

Proton-driven plasma wakefield acceleration

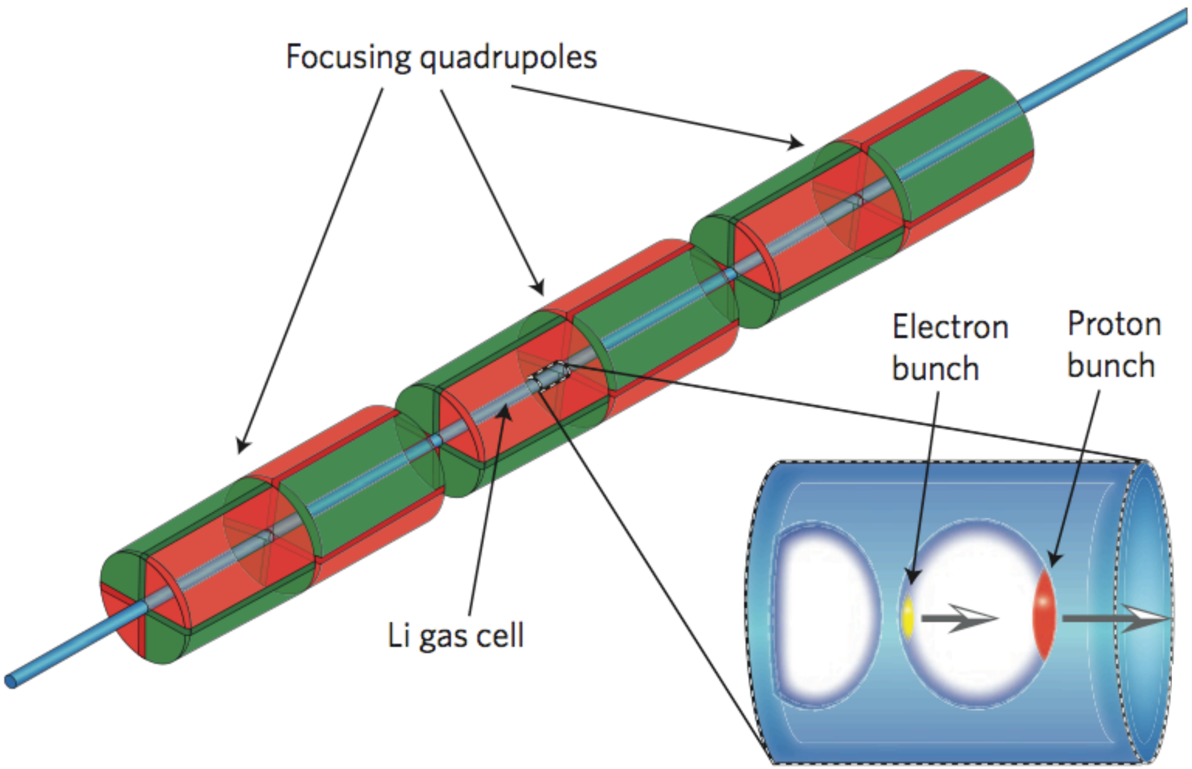
Plasma wakefield experiments

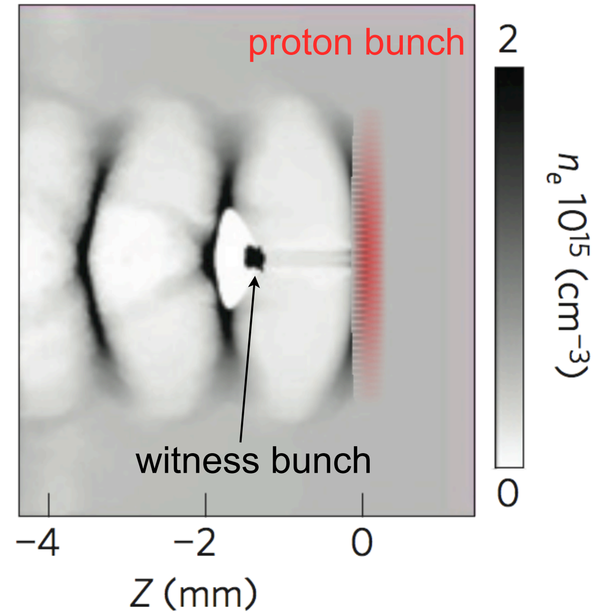
- Pioneering work using a LASER to induce wakefields.
- Experiments at SLAC§ have used a particle (electron) beam :
    - Initial energy E_e = *42 GeV*
    - Gradients up to ~ *52 GV/m*
    - Energy doubled over ~ *1 m*
- Have proton beams of much higher energy :
    - HERA (DESY) : 1 TeV
    - Tevatron (FNAL) : 1 TeV
    - CERN : 24 / 450 GeV and 7 TeV

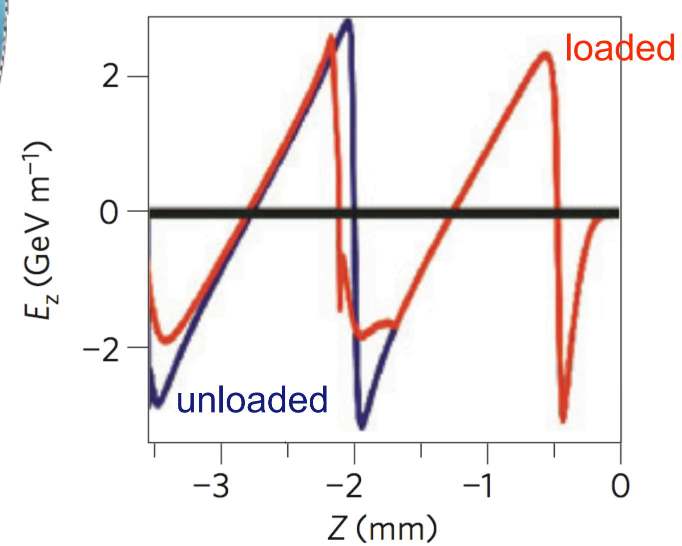


§ I. Blumenfeld et al., Nature **445** (2007) 741.

PDPWA concept*





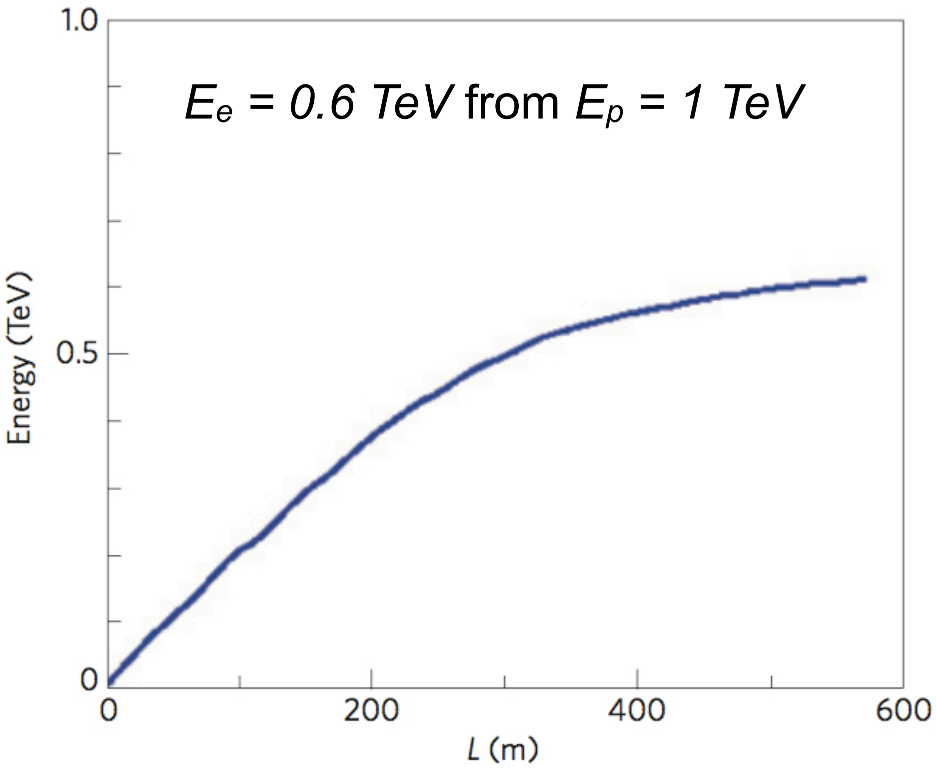


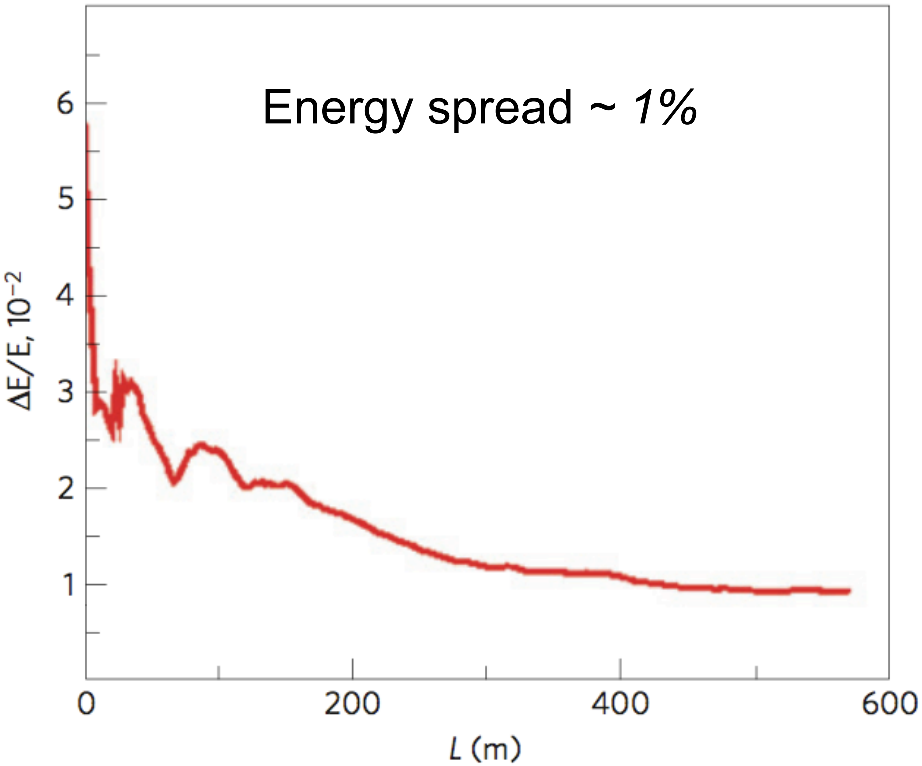
- Electrons 'sucked in' by proton bunch.
- Continue across axis creating a depletion region.
- Transverse electric fields focus witness bunch.
- Maximum accelerating gradient of 3 GV/m.

* A. Caldwell *et al.*, Nature Physics **5** (2009) 363.

PDPWA concept

Proton beam impacting on a plasma to accelerate and electron witness beam





PDPWA concept

Table 1 | Table of parameters for the simulation.

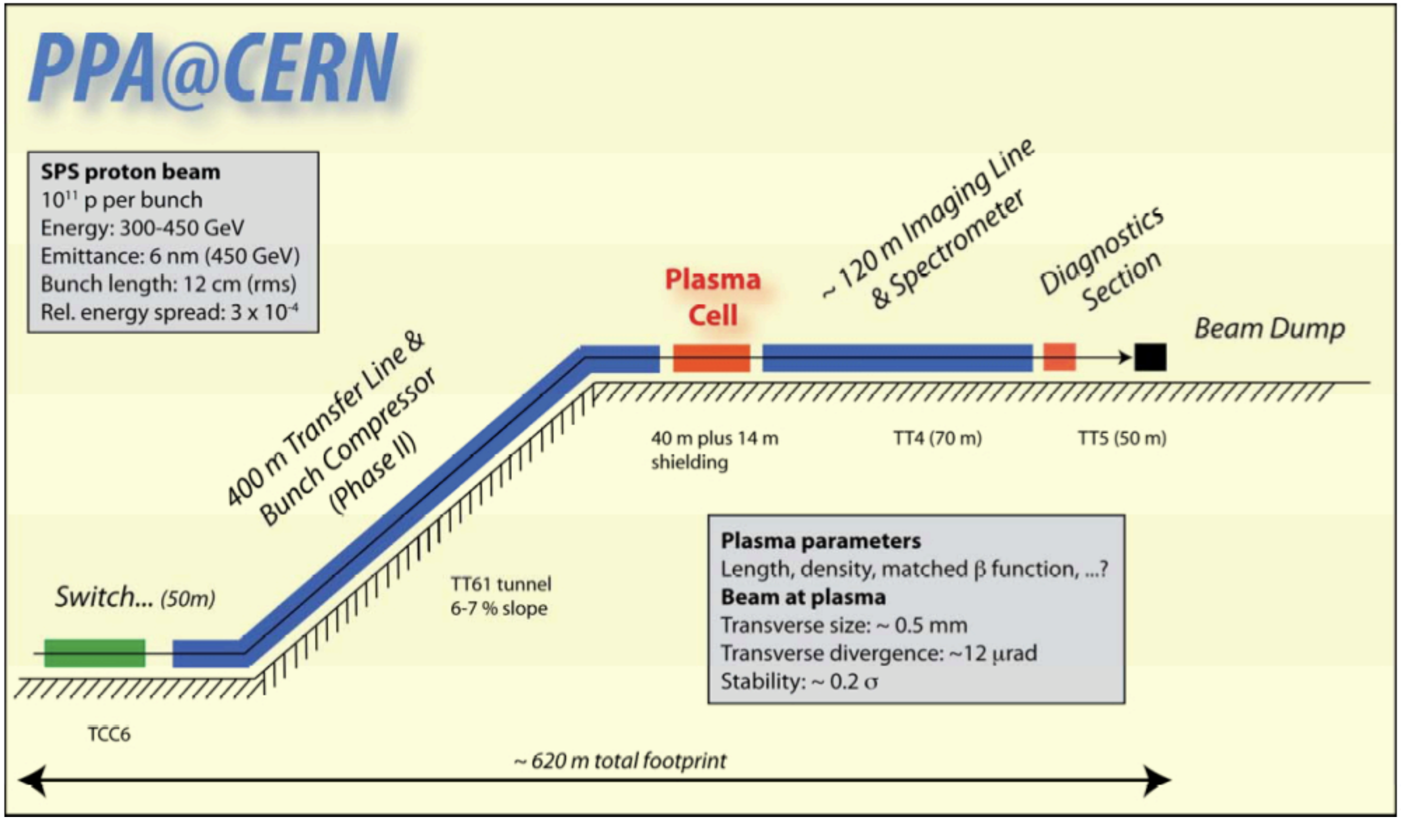
Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	$\mathrm{T\,m}^{-1}$
Magnet length		0.7	m

• Would need significant bunch compression < *100 µm* (or new proton source).

• Challenges include : sufficient luminosities for an e^+e^- machine, repetition rate, focusing, accelerating positrons, etc..

Towards a test experiment

Proposed experiment at CERN



Near-term (5-year) plan :

- Achieve > *1 GeV* energy self-modulation of proton beam in ~ *5 m* plasma.
- Possible acceleration of witness electrons.

PDPWA Collaboration and practicalities

Collaboration of accelerator, plasma and particle physicists and engineers being formed :

- Led by A. Caldwell (MPI Munich).
- Institutes from Germany, Portugal, Russia, Switzerland, USA and UK.
- UK interest from Cockcroft, Imperial, JAI/Oxford, RAL, UCL.
- Letter of Intent to be prepared for CERN SPSC.
- Plan for a 5-year experiment with support from CERN and its accelerator division.
- HERA, Tevatron and LHC beams can not be used. Possibility of PS (24 GeV) or SPS (450 GeV) proton beam.
- Collaborating institutes will need to provide (in-kind) resources of e.g. magnets, experimental equipment, e.g. plasma cell, and effort to run and analyse.

Simulation of PDPWA

• Various codes have been used : 2D fluid LCODE [Lotov], 3D PIC VLPL [Pukhov], 3D PIC OSIRIS [Hemker et al.], 3D quasi-static QuickPIC [Huang et al.].

• Fixed and representative parameters for code benchmarking.

• Initial Gaussian and half-cut beam.

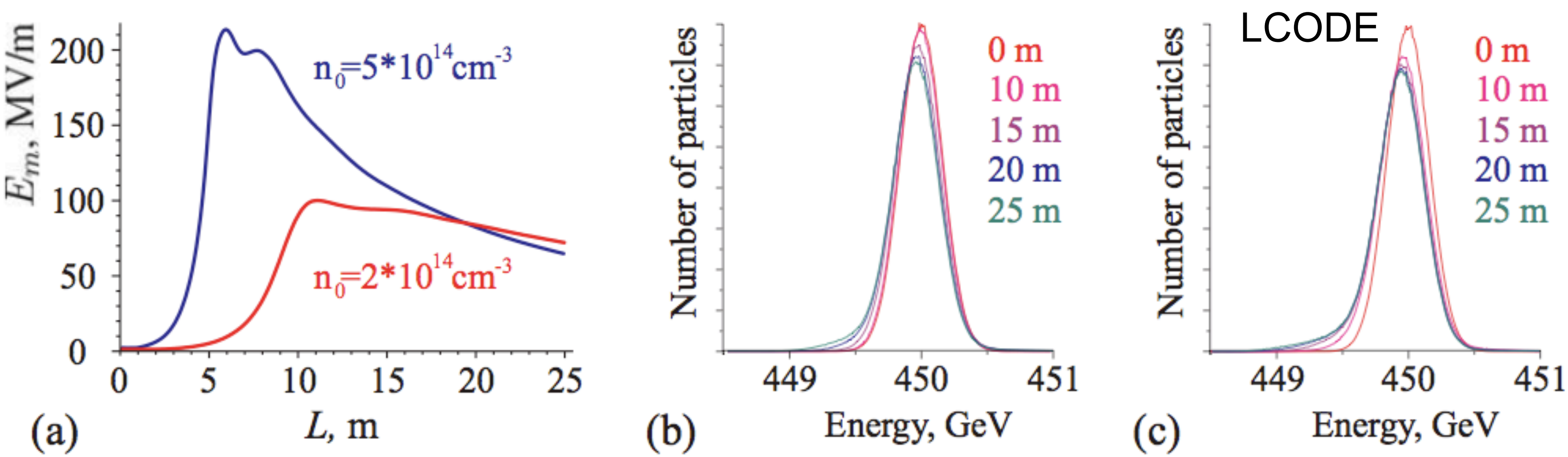
Table 1. Parameter Sets for simulation comparison.

Parameter	Set 1 (PS)	Set 2 (PS-high n_p)	Set 3 (SPS)	Set 4 (SPS-high n_p)	Set 5 (SPS-Totem)
Beam energy E_p (GeV)	24	24	450	450	450
Bunch intensity N_p (10^{10})	13	13	11.5	11.5	3.0
Energy deviation σ_p (MeV)	12	12	135	135	80
Bunch length σ_z (cm)	20	20	12	12	8
Beam size σ_r (μm)	400	400	200	200	100
Beam divergence σ_θ (mrad)	0.25	0.25	0.04	0.04	0.02
Plasma density n_p (cm^{-3})	10^{14}	$3 \cdot 10^{14}$	10^{14}	10^{15}	10^{15}
Plasma length L_p (m)	10	10	10	10	10

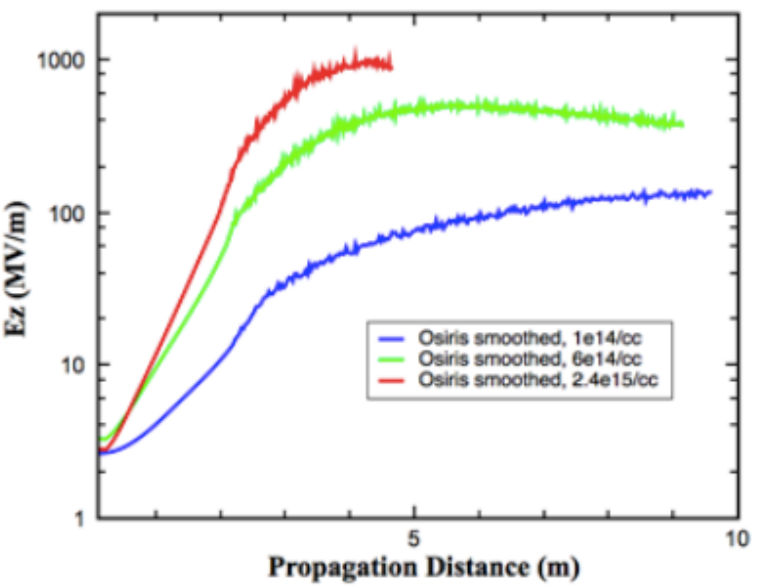
• Results focus on Set 3 which is most realistic and SPS beam preferred.

• Note proton bunch length compared to concept. Beam compression expensive

Simulation results for Set 3



- ~ 100 MV/m for Set 3, reasonably consistent between codes.
- Higher plasma density gives values up to 1 GV/m.
- Possibility to gain high proton density at the cost of having a single bunch mode.

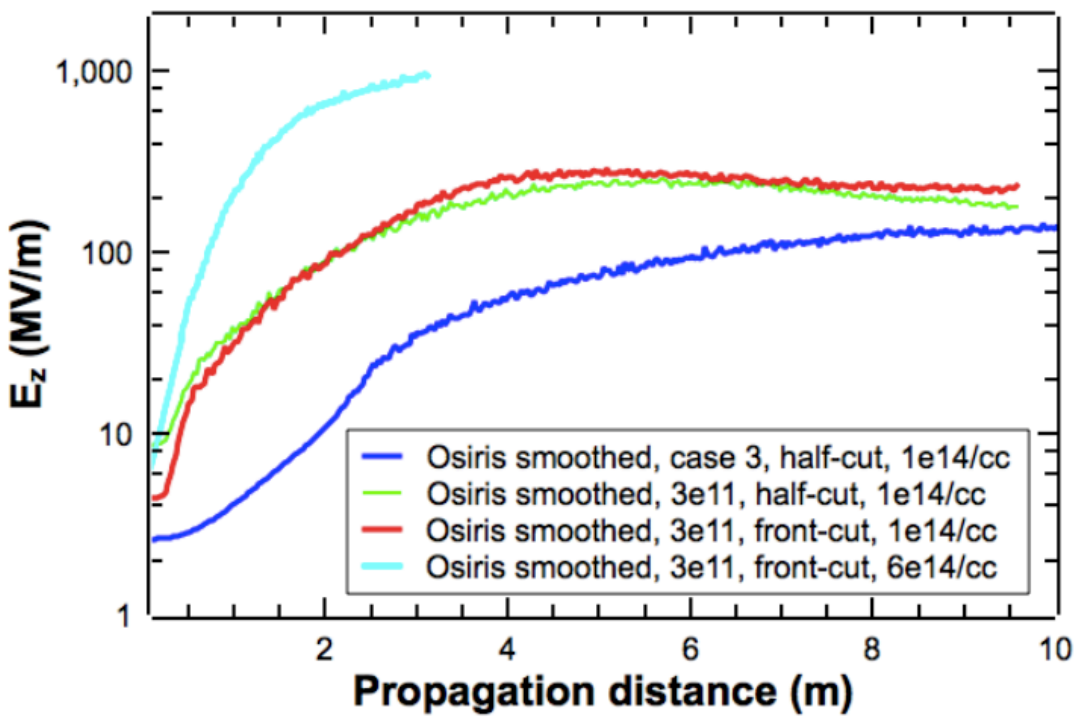


Single-shot mode

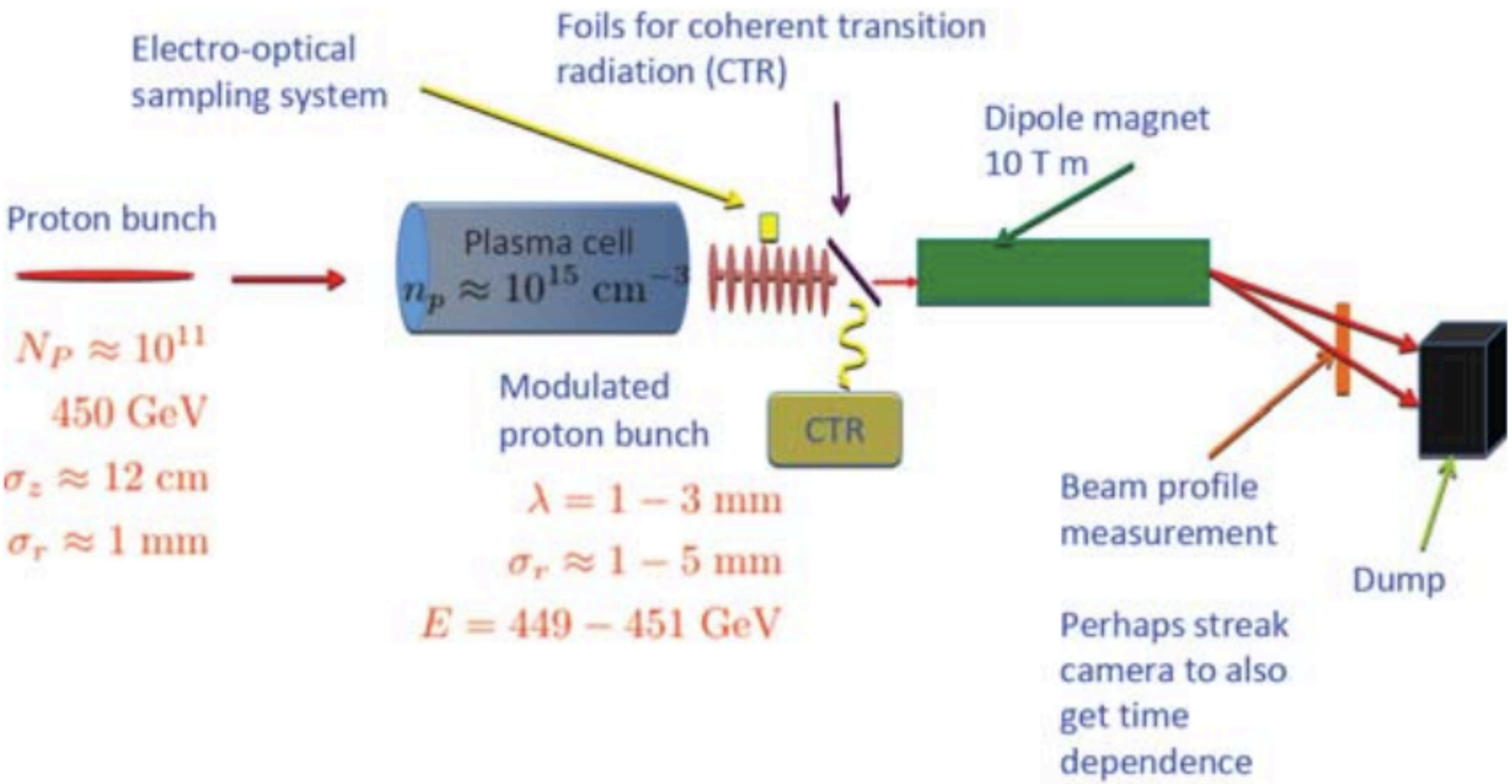
Bunch population, N_p	$3x10^{11}$
Bunch length, σ_z	8.5 cm
Beam radius,$\sigma_{x,y}$	200 µm
Beam energy, E	450 GeV
Energy spread, dE/E	0.04%
Normalized emittance, $\varepsilon_{x,y}$	2 µm
Angular spread, σ_θ	0.02 mrad

Possibility to tune/upgrade beam parameters such as population and bunch length.

- Electric field about twice as high as for Set 3.
- Reach up to 1 GV/m for lower plasma density.
- Further optimisation of beam and plasma parameters ongoing.



Beamline design and diagnostics



- Study in detail interaction of proton beam and plasma.
- Benchmarking of PIC simulation against experimental data.
- Beam and plasma diagnostic tools to be developed.

Beamline design and diagnostics

- Spectrometer magnet to measure small deflection of beam and determine energy—looking for ~GeV change in proton beam above beam spread (0.15 GeV). Electrons easier.
- Need diagnostics to :
  - characterise the plasma;
  - characterise the proton beam before, in and after the plasma cell and without the plasma cell;
  - characterise witness electrons.
- As much redundancy as possible, various techniques :
  - wire scanners or optical transition radiation to measure transverse profile;
  - optical transition radiation with cameras to measure bunch length;
  - electro-optic sampling measuring the change in refractive index of a crystal due to the passage of the beam.

Future plans and challenges

Future experimentation

- The idea of proton-driven wakefield acceleration will follow a staged approach.
- If first experiment successful, then move onto :
  - Reach an energy gain of 100 GeV over 100 m;
  - Intermediate stage to possible “full” experiment;
  - Need to move to higher efficiency non-linear regime;
  - Requires significantly compressed proton beam—magnetic compression, cutting the beam into slices, etc..
- Ultimate goal of application to a TeV-scale lepton collider.

The far future

- A TeV e^+e^- linear collider *O(km)* long
- But hopefully not too "far" !

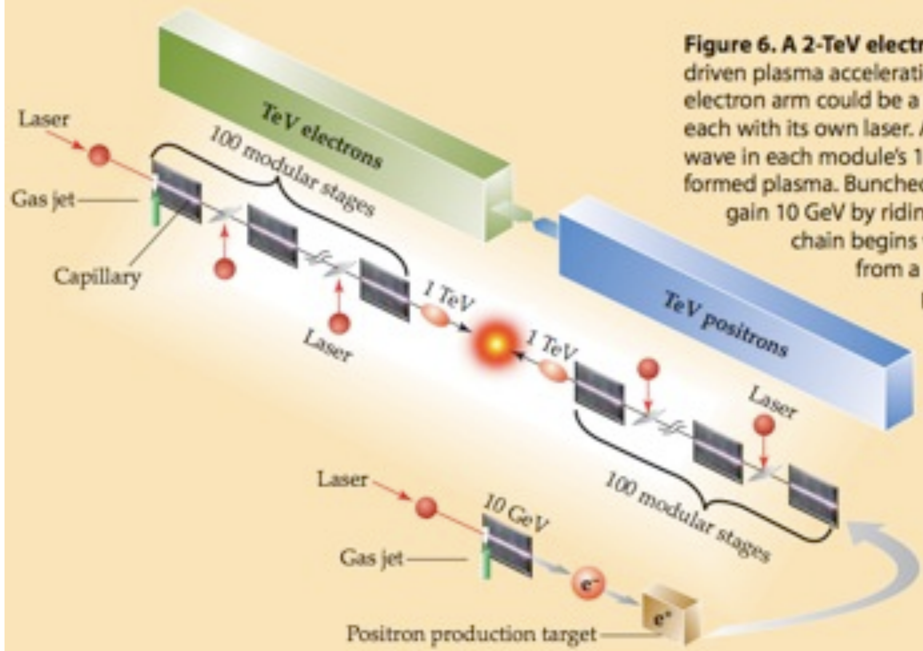


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of preformed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans, E. Esarey, Physics Today, March 2009

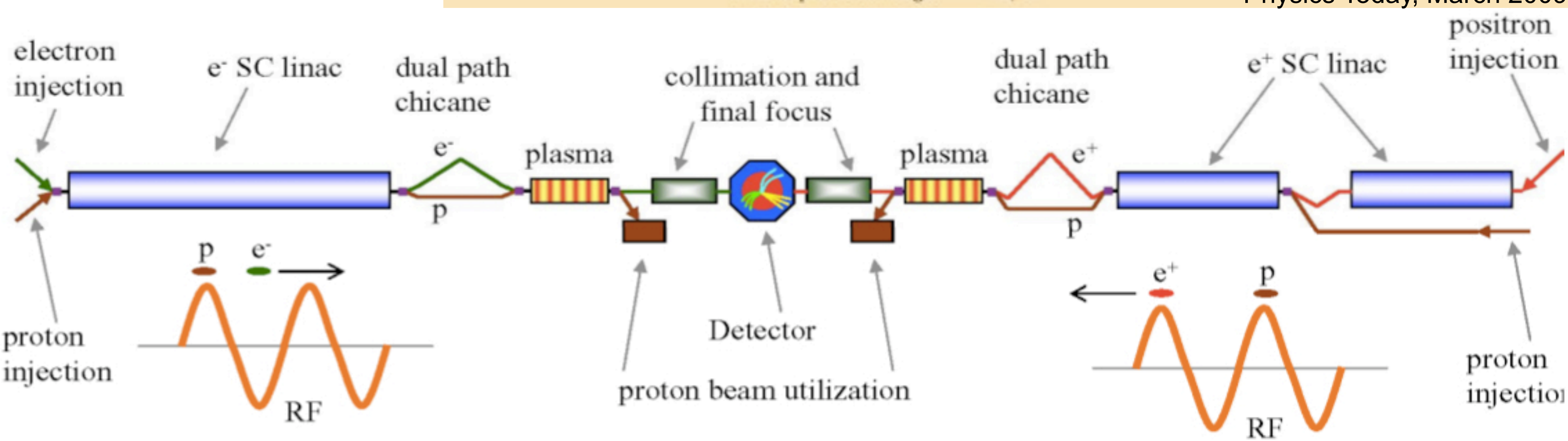


Figure 1: Concept for a multi-TeV upgrade of the International Linear Collider based on proton-driven plasma acceleration. The phase slippage controlling chicanes within the linacs are not shown. Not to scale.

A. Seryi, ILC-Note-2010-052

Summary

- Presented an idea to have a high energy lepton collider based on proton-driven plasma wakefield acceleration.
- Has interest and needs input from accelerator, plasma and particle physics.
- Proof-of-principle experiment being proposed.
- Many challenges : beam sizes, long plasma cells, rates, etc..
- To realise a TeV-scale lepton collider a factor of ~ 10 shorter than current designs.